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14. ABSTRACT We elucidated search algorithms used by benthic marine animals (mantis shrimp) when finding an odorant source in wave-influenced coastal flow versus in unidirectional flow. We did so by quantifying animal behavior when finding odorant sources in waves versus unidirectional flow in a flume while simultaneously using planar laser-induced fluorescence (PLF) to quantify the instantaneous concentration structure of the odor plume around the olfactory when the animals execute specific behaviors. The search rules we discovered (relating behaviors to the instantaneous plume environment near sensors) can be implemented in artificial systems operating in coastal environments.						
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FINAL REPORT

GRANT #: N00014-98-1-0775

PRINCIPAL INVESTIGATOR: M. A. R. Koehl

INSTITUTION: University of California at Berkeley

GRANT TITLE: Animal Plume-Tracing Behavior in Wave Influenced Flow Domains

AWARD PERIOD: 7/01/98 - 6/30/01

OBJECTIVE: Our objective is to elucidate search algorithms used by benthic marine animals (mantis shrimp) when finding an odorant source in wave-influenced coastal flow versus in unidirectional flow. Such search rules (relating behaviors to the instantaneous plume environment near sensors) can be implemented in artificial systems operating in coastal environments.

APPROACH: We videotaped stomatopod behavior when finding odorant sources in waves versus unidirectional flow in a flume while simultaneously using planar laser-induced fluorescence (PLF) to quantify the instantaneous concentration structure of the odor plume around the antennules when the animals execute specific behaviors. Our flume flow conditions were based on our measurements of water flow in stomatopod habitats, and the odorant concentrations used were based on our y-maze experiments of stomatopod plume-tracing.

ACCOMPLISHMENTS: We determined the fine spatial and temporal scale of concentration fluctuations at which stomatopod antennules encounter odor plumes by using PLF and high-speed, high-magnification video of antennules on a stationary body as they flicked in waves versus in unidirectional flow in the Stanford flume (Koseff's group used our field velocity measurements to design relevant flow in their flume). We conducted a series of y-maze experiments to quantify the concentrations of odorant to use in our flume behavior experiments. We then used PLF to quantify the instantaneous plume concentration distributions at antennules during behavior experiments when the animals searched for a momentumless odor source in the flume in waves versus unidirectional flow. We simultaneously recorded stomatopod behavior (locomotory speed, orientation, location and frequency of antennule flicking) while searching for plumes, relocating lost plumes (plumes meander), odor tracking within plumes, and locating the source when very near to it (when the odor is in the viscous sublayer). We found that odor plumes in both waves and in unidirectional flow are composed of fine filaments of high concentration interspersed with patches of clean water, and that stomatopods sample the water around them in a pulsatile way by flicking their olfactory antennules. When stomatopods encounter odor filaments with their antennules while plume tracking, the filaments are more numerous, have a higher odor molecule concentration, and are wider in wave-affected flow than in unidirectional flow. In both wavy and in unidirectional flows, animals use the same plume-locating and plume-tracing algorithms: 1) move perpendicular to the flow direction until odor filaments are encountered, and then turn upstream; 2) move back and forth across the plume, heading upstream at an angle of approximately 45 degrees to the flow direction ("casting" behavior), narrow the cast as closer to the source (where the plume gets narrower), and 3)

sample the water with olfactory sensors held high until near the benthic source (where the plume height is small); then sample with sensors close to the substratum.

SIGNIFICANCE: We are quantifying search algorithms used by benthic marine animals when finding an odor source in the oscillatory flow of waves as well as in unidirectional currents. Although animals and automated plume-tracing devices using water-borne chemical cues to locate objects in shallow coastal sites must find odorant sources in waves, plume-tracking studies before ours focused on unidirectional flow. By quantifying the instantaneous plume environment around the olfactory antennules of the animals while simultaneously measuring the behaviors that they execute, we are elucidating search rules that can be implemented in artificial systems designed to operate in coastal environments. The search algorithms we are working out for marine organisms finding odor sources in wave-driven flow, which is typical of shallow marine environments, should be useful in developing search algorithms for man-made vehicles and robots searching for odor sources in coastal areas. In addition, the information we are gathering about how the hydrodynamic design and deployment of olfactory antennules affects the spatial and temporal scales of odorant capture should provide valuable information for the design of man-made olfactory sensors.

AWARD INFORMATION:

Mimi Koehl (P.I.):

Awards and Honors, 1998 - 2002:

Phi Beta Kappa Visiting Scholar, 1998-1999
Distinguished Alumni Award, Gettysburg College, 1998
President, Western Society of Naturalists, 1999
Miller Professorship, 2001
National Academy of Sciences, elected 2001
American Academy of Arts & Sciences, elected 2002
Borelli Award, American Society of Biomechanics 2002 (for
"outstanding career accomplishment" and "exemplary
contributions to the field of biomechanics")

Honorific Lectures, 1998 - 2002:

Plenary Lecturer, Oceanographic Society & IOC Meeting, Paris, 1998
Keynote Speaker, Engineering Found'n International Symposium, 1998
Weise Lecturer, Dauphin Island Marine Laboratory, 1999
Keynote Lecturer, Symposium in Nonlinear Biology, 1999
Illg Memorial Lecturer, Friday Harbor Laboratories, 1999
Ian Morris Scholar, Horn Point Laboratory, University of Maryland
Distinguished Speaker, International Workshop on Biofluidynamics
in Memory of Sir James Lighthill, Israel
Keynote Speaker, Plant Biomechanics Conference, Germany, 2001
Plenary Lecturer, Aquatic Sciences Meeting, 2001
Laura Schwepp Lecture, Marine Science Institute, Univ.Texas, 2002

Recognition in the Media and Popular Press, 1998 - 2002:

Koehl research featured in BBC science documentary in the series
"Biology: Uniformity and Diversity"
Research Kate Loudon and I did on the fluid dynamics moth
antennae was featured in "Editor's Choice" in *Science*
Research on how olfactory antennules capture odor signals from
turbulent currents that I did with J.Koseff was featured on
television (Canadian Discover, Tech TV), radio (PBS "Todd Mundt

Show"; CBC "Quirks and Quarks"), and in many newspaper (e.g. New York Times) and magazine articles (e.g. Natural History)

Marlene Martinez (graduate student):

Outstanding Graduate Student Instructor Award, U.C. Berkeley, 1999

Michael McCay (graduate student):

Dwight Davis Award, Soc. Integrative & Comparative Biology, 1999

Outstanding Graduate Student Instructor Award, U.C. Berkeley, 1999

Gaige Fund Award, ASIH, 1999.

Matthew McHenry (graduate student):

Best Student Paper Award, Soc. Integr. & Comp. Biology, 2000, 1998

Adrian Wenner Strong Inference Award, Soc. Integr. & Comp. Biology, 2000

Dwight Davis Award, Soc. Integr. & Comp. Biology, 2000, 2002

Kimberly Quillin (graduate student):

Best Student Paper Award, Soc. Integrative & Comparative Biology, 1998

Certificate of Recognition, NASA Inventions & Contributions Board. (1998)

Winnie Lau and Jeff Goldman (undergraduates): Graduated with Honors,

PUBLICATIONS AND ABSTRACTS:

Koehl (P.I.):

(Due to page limits, no abstracts or "in prep." papers are listed):

1. Koehl, M. A. R. (1998) Small-scale hydrodynamics of feeding appendages of marine animals. *Oceanography* **11** : 12 -14.
2. Shimeta, Jeff and M. A. R. Koehl (1997) Mechanisms of particle selection by tentaculate suspension feeders during encounter, retention, and handling. *J. Exp. Mar. Biol. Ecol.* **209**: 47-73.
3. Koehl, M .A. R. (1998) Small-scale hydrodynamics of particle and odorant capture by animals. (abstract) *Oceanography* **11**: 20.
4. Koehl, M. A. R. (2000) Consequences of size change during ontogeny and evolution. pp. 67-86 In Scaling in Biology. J.H.Brown and G. B.West [eds.], Oxford University Press, NY.
5. Dickinson, M.H., Farley, C.T., Full, R.J., Koehl, M.A.R., Kram, R., and Lehman, S. (2000) How Animals Move: An Integrative View. *Science* **288**: 100-106
6. Loudon, C. and M. A. R. Koehl (2000) Sniffing by a silkworm moth: Wing fanning enhances air penetration through and pheromone interception by antennae. *J. Exp. Biol.* **203**: 2977-2990.
7. Koehl, M.A. R. (2001) Fluid dynamics of animal appendages that capture molecules: Arthropod olfactory antennae. pp.97-116 In, Computational Modeling in Biological Fluid Dynamics. L. Fauci and S. Gueron [eds.], IMA Series #124.
8. Goldman, J. A. and M. A. R. Koehl (2001) Fluid dynamic design of lobster olfactory organs: High-speed kinematic analysis of antennule flicking by *Panulirus argus*. *Chemical Senses* **26**: 385-398.
9. Koehl, M. A. R. (2001) Transitions in function at low Reynolds number: Hair-bearing animal appendages. *Math. Meth. Appl. Sci.* **24**: 1523-1532.
10. Koehl, M. A. R., J. R. Koseff, J. P. Crimaldi, M G. McCay, T. Cooper, M. B. Wiley, and P. A. Moore (2001) Lobster sniffing: Antennule design and hydrodynamic filtering of information in an odor plume. *Science*. **294**: 1948-1951
11. Stacey, M., K. S. Mead, and M. A. R. Koehl (2002) Molecule capture by olfactory antennules: Mantis shrimp. *J. Math. Biol.* **44**: 1-30.
12. Crimaldi, J. P., M. A. R. Koehl, and J. R. Koseff (2002) Effects of

the resolution and behavior of olfactory appendages on the chemical signals they intercept in a turbulent odor plume.
Environ. Fluid Mech. (in press).

13. Koehl, M. A. R. Modeling in Biomechanics. Phil. Trans. Roy. Soc. B
(submitted)

Mead (Postdoctoral Scholar): (Due to page limit, only abstracts published in journals are listed and no "in prep." papers are listed.)

14. Mead, K.S. (1998) The biomechanics of odorant access to aesthetascs in the grass shrimp, *Palaemonetes vulgaris*. Biol. Bull. 195: 184-185.

15. Mead, K.S. (1998) Size, speed, and stink: How the boundary layer surrounding stomatopod chemosensory setae during olfactory flicking changes as the animals grow. Am. Zool. 38: 82A

16. Mead, K. S., M. A. R. Koehl, and M. J. O'Donnell (1999) Stomatopod Sniffing: The scaling of chemosensory sensillae and flicking behavior with body size. J. Exp. Mar. Biol. Ecol. 241: 235-261.

17. Mead, K.S. and M.A.R. Koehl (2000) Stomatopod antennule design: The asymmetry, sampling efficiency, and ontogeny of olfactory flicking. J.Exp.Biol. 203: 3795-3808.

18. Mead, K. S. (2000) An interdisciplinary, multilevel approach to olfaction in stomatopods. Am. Zool. 40: 1127.

19. Mead K. S. and Wiley, M. B. (2002) How do benthic crustaceans trace odor plumes in waves?: Integrating fine-scale odor structure with animal behavior. Am. Zool. 41: 1523A

20. Mead, K. S. (2002) From odor molecules to plume tracing: an interdisciplinary, multilevel approach to olfaction in stomatopods. J. Comp. Int. Biol. 42: 1562A.

21. Mead, K. S. (2002) Using lobster noses to inspire robot sensor design . Trends in Biotechnology. DOI: 10.1016/S0167-7799(02)01979-0

22. Mead, K.S. and T. M. Weatherby (2002). The morphology of stomatopod chemosensory sensilla facilitates fluid sampling. Inv.Biol. 121: 148-157

23. Mead, K.S., M.B. Wiley, M.A.R. Koehl, and J.R. Koseff (2002) Fine-scale patterns of odor encounter by olfactory antennules of a crustacean tracking a turbulent odor plume in wave-affected and unidirectional flow. J. Exp. Biol. (submitted)

Student Papers and Abstracts (An additional 7 papers and 6 abstracts published in scientific journals by my graduate students that were supported by an AASERT grant associated with this ONR grant are listed in the final report for the AASERT: ONR Grant # N00014971026)(Due to page limit, only abstracts published in journals are listed and no "in prep." or "submitted" papers are listed.)

24. McHenry, M. J.(2001) Mechanisms of helical swimming: asymmetries in the morphology, movement and mechanics of larvae of the ascidian *Distaplia occidentalis*. J. Exp. Biol. 204: 2959-2973

25. Stewart, H. L. (2002) Hydrodynamic consequences of buoyancy and flexural stiffness in benthic algae. Eos. Trans. AGU. 83(4), Ocean Sciences Meet. Suppl., Abstract OS41K-10

26. Stewart, H. L. (2000) Morphological heterogeneity among zooids of encrusting colonies of *Membranipora membranacea* induces passive flow through the colony. Am. Zool. 40(6): 1223A